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## SEMICONDUCTOR DEVICE CONCEPTS

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### Abstract

Generation of coherent visible radiation in  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  p-n junctions is described. The conditions for generation of coherent visible radiation, the possibilities of wavelength selection, and the extension to and implications of p-n junction lasers in ternary compounds are presented.

The electrical properties of  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  p-n junctions and their considerable potential for use as avalanche and forward regulator diodes, signal diodes, parametric diodes, and stored charge diodes are described.

#### A. Coherent (Visible) Light Emission from $\text{Ga}(\text{As}_{1-x}\text{P}_x)$ Junctions

Recently Hall, Fenner, Kingsley, Soltys, and Carlson<sup>1</sup> (HFKSC) have reported generation of coherent infrared radiation from forward biased GaAs p-n junctions. In this communication we wish to report similar generation of shorter wavelength (visible) coherent radiation from forward biased  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  p-n junctions. As in the experiments reported by Hall, et al, evidence for coherent light emission in  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  is based upon the observation of a threshold current beyond which the light intensity increases sharply, upon the pronounced narrowing of the spectral distribution of emitter light beyond threshold, and upon the sharply beamed radiation pattern of the emitted light. Again, as in the case described by HFKSC, the stimulated emission is believed to occur as the result of transitions between states of equal wave number in the conduction and valence bands. It is believed this circumstance obtains because of the choice of the ratio of P to As in  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  so that the crystal is a "direct" semiconductor.<sup>2</sup>

In the present case the conditions on a) junction design and doping, b) degree of inversion (by injection) of carriers in conduction band and valence band states in the junction transition region, and c) geometrical relationship of the junction plane to the bounding, parallel "cavity" faces for stimulated emission are as described in reference 1.

Our  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  diodes are rectangular parallelepipeds or cubes with two opposite, parallel sides carefully polished and with an active (junction) area  $\sim 10^{-3} \text{ cm}^2$ . In each diode a diffused junction lies  $10\mu$  or deeper from one contact surface into the crystal and is perpendicular to the two polished surfaces. Most of our diodes have been fabricated on n-type  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  prepared by the halogen vapor transport and synthesis procedure we have previously described<sup>3</sup>. Donor impurity concentrations greater than  $10^{18}/\text{cm}^3$  have been employed.

Electrically, the diodes have "clean" V-I characteristics and rise steeply into forward conduction on a scale comparable to that of high quality GaAs p-n junctions. As expected, because of the larger (variable) bandgap of  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$ , the diodes require higher forward voltages than GaAs junctions, e.g. 1.3 volts (diode 28A) as compared to 1.0 volt at the "corner" leading to steep current increase. The overall high quality and efficiency of these junctions is indicated by the fact that in free air ( $300^\circ\text{K}$ ) currents from 20 mA to over 100 mA do not overheat the junctions, and are sufficient to produce easily perceptible red light emission.

The evidence for stimulated emission may be conveniently presented by referring to Fig. 1, which represents data taken on diode 28A while immersed in liquid nitrogen. Below  $\sim 11,000 \text{ amp/cm}^2$  the light intensity varied linearly with current (pulsed-current, pulses 1 to 5  $\mu\text{sec}$  long). Above  $\sim 11,000 \text{ amp/cm}^2$  the light intensity increased sharply with current (super-linear region), and began to assume a narrower pulse width than the somewhat rounded input current pulse. This threshold behavior characterizes the onset of stimulated emission.

As shown by curve a) of Fig. 1 the spectral width below or near threshold ( $11,000 \text{ amp/cm}^2$ ) was  $\sim 125 \text{ \AA}$ . Although it is not shown on Fig. 1, the spectral width at  $16,000 \text{ amp/cm}^2$  narrowed to  $\sim 20 \text{ \AA}$  and, as shown by curve b), narrowed to  $\sim 12 \text{ \AA}$  at  $19,000 \text{ amp/cm}^2$ . This, also, is consistent with the onset of stimulated emission. Whereas the GaAs junctions described by Hall, et al emitted coherent radiation near  $8400 \text{ \AA}$ , it will be noticed that for diode 28A we have been able to shift the wavelength to a sharply peaked output at  $7100 \text{ \AA}$ .

The radiation pattern from diode 28A was observed in the manner described by Hall, et al and exhibited the same general geometrical and diffraction features<sup>1</sup>, thus substantiating the existence of coherent emission.



These and related results on other  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  diodes, and their complete consistency with those of Hall, et al, add confirmation and further weight to the generality with which stimulated emission may be produced in various semiconductors. Specifically, our results in  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  show that a p-n junction laser can be built with an output wavelength which can be selected in the range from perhaps below 6200 Å (2.0 eV) to near 8400 Å (1.48 eV). The fact that we observe stimulated emission and a very sharply peaked output from  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  p-n junctions implies a well defined band structure, which in turn supports the idea that the random distribution of As and P in  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  has little or no effect in "smearing" band properties.

## B. Electrical Properties of $\text{Ga}(\text{As}_{1-x}\text{P}_x)$ p-n Junctions

In an earlier communication<sup>4</sup>, and in the previous section, we have mentioned briefly that  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  p-n junctions have been fabricated, mainly as junction luminescent sources (visible, incoherent and coherent), which exhibit high quality electrical characteristics. The purpose of this section is to describe and draw attention to specific V-I characteristics and electrical properties of  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  p-n junctions which make them excellent candidates for use as signal diodes, voltage regulator diodes, and possibly parametric and stored charge diodes.

A typical characteristic of a type which has been obtained in numerous  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  crystals synthesized by means of halogen vapor transport processes<sup>3</sup> is shown in Fig. 2. The p-n junction whose characteristics are shown in Fig. 2 was prepared by diffusing a  $\sim 20 \mu$  deep p-layer into n-type  $\text{Ga}(\text{As}_{0.67}\text{P}_{0.33})$  doped with  $10^{18}$  donors/cm<sup>3</sup>. A mesa p-n junction structure was prepared of roughly  $0.5 \times 10^{-3} \text{ cm}^2$  area and zero-bias capacitance of  $75 \mu\text{f}$  (estimated junction width  $\sim 750 \text{ \AA}$ ). Considerably smaller structures of  $\sim 5 \mu\text{f}$  capacitances and forward characteristics as steep or steeper than comparable silicon junctions also have been prepared.

In the reverse direction as shown in Fig. 2 sharp avalanche properties are observed with the breakdown voltage, as expected, decreasing as temperature is decreased. Depending upon the crystal, its arsenic-phosphorus ratio, donor concentration, and diffused junction depth, we have observed sharp avalanche breakdown in the range from 17 V to almost 5 V. At present we are not certain that  $\sim 5 \text{ V}$  is a lower limit on avalanche breakdown, which raises the interesting possibility that  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  may afford a considerably lower avalanche voltage limit than silicon.

In the reverse direction leakage currents of  $\sim 10^{-12}$  A or less are easily obtained (300°K).

As is clear in Fig. 2 the "knee" or "corner" leading to steep forward conduction occurs at higher voltages (1.3 V) than in GaAs, and obviously considerably higher than Si. Depending upon the unit, i.e. depending upon primarily the arsenic-phosphorus ratio, at room temperature we have observed voltages in the forward conduction region from 1 V (GaAs) to over 1.5 V ( $\text{Ga}[\text{As}_{1-x}\text{P}_x]$ ). These relatively high voltages coupled with quite steep forward characteristics (p+n+ construction) make it possible for  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  junctions to be applied as low voltage regulators. Also, the relatively high voltages required for forward conduction make possible parametric diodes which in some cases could be operated under conditions of zero DC bias and still allow a significant dynamic operating range.

Finally, measurements by T. P. Sylvan indicate that diffused p+n+  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  diodes can exhibit considerable stored charge, possibly due to appreciable high level minority carrier lifetime and an advantageous structure (i.e. degenerate end regions juxtaposed on either side of a thin transition region), and consequently may show promise in applications requiring generation of fast pulses.

### Contributors

Individuals who contributed to the contract activity in this period are:

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A number of the measurements reported in section A were supplied by J. D. Kingsley and G. E. Fenner (Schenectady).

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4. N. Holonyak, Jr. and S. F. Bevacqua, "Coherent (Visible) Light Emission From Ga(As)<sub>1-x</sub>P<sub>x</sub> Junctions", Appl. Phys. Letters, vol. 1; December, 1962.

### Figure Captions

Fig. 1 Spectral distribution of  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  diode 28A at  $77^\circ\text{K}$ . a) Below threshold ( $11,000 \text{ amp/cm}^2$ ) and b) above threshold ( $19,000 \text{ amp/cm}^2$ ). Different vertical scales.

Fig. 2 V-I characteristics of visible light (red) emitting  $\text{Ga}(\text{As}_{1-x}\text{P}_x)$  pn junction,  $x \approx 0.33$ . Junction (diffused) depth  $\sim 20 \mu$ , crystal substrate n-type doped  $\sim 10^{18} \text{ donors/cm}^3$ , zero-bias capacitance 75 pf.

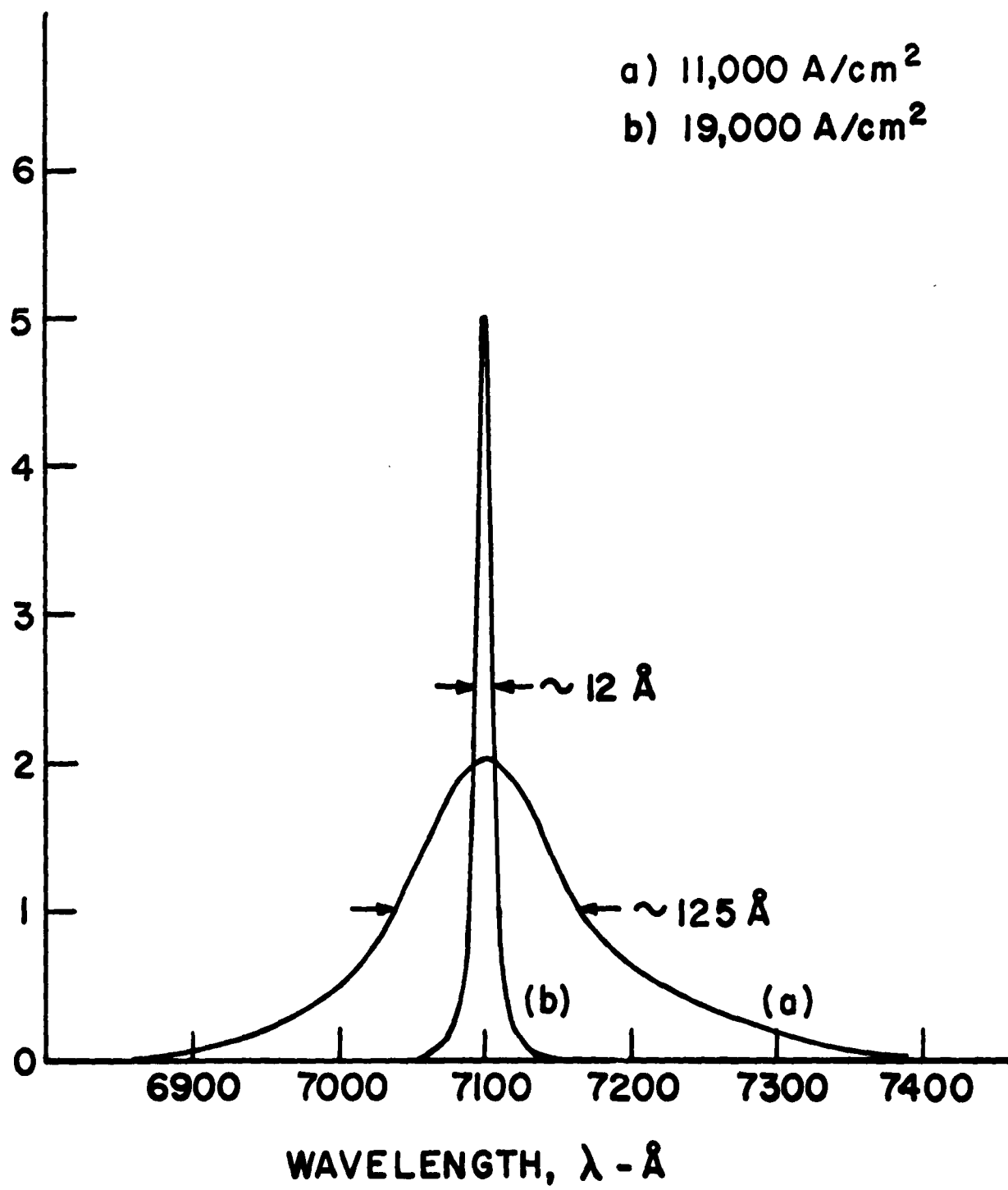


Fig. 1

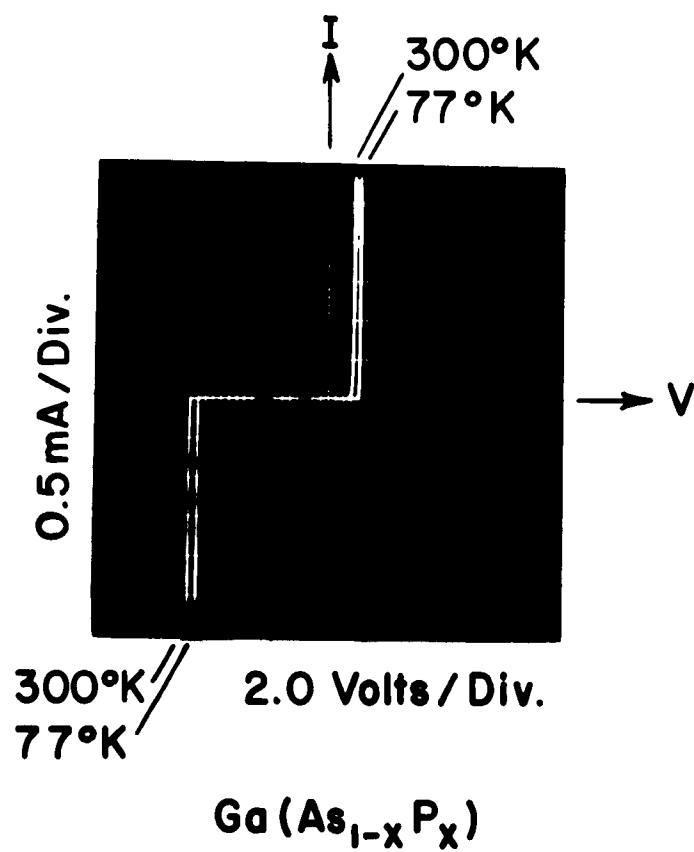


Fig. 2



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